



MICHIGAN STATE UNIVERSITY

The Future of Batteries for Transportation

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The Physical, Chemical and Technological Aspects of the
Fundamental Transition in Energy Supply from Fossil to
Renewable Sources – Key Aspect: Energy Storage

791. WE-Heraeus-Seminar



CO₂ Emission from Transportation: USA

- Gasoline consumption per day: 350 million gallons (1.35 billion liters)
- Diesel fuel consumption per day: 120 million gallons (460 million liters)
- Contributes 1.6 giga-tons of CO₂ emission per year
 - ¼ of total US emissions
 - 10% of annual global net addition of CO₂ to Earth's atmosphere

Conversion to battery-powered electric vehicles is imperative



Battery Performance Characteristics

- Volumetric energy density [Wh/L]
- Gravimetric energy density [Wh/kg]
- Cycle efficiency
- Battery life
 - Number of charge cycles
 - Degradation per charge cycle
- Maximum charging power
- Temperature dependence
- Price
- Raw materials
 - Recyclability
 - Availability



Side note: Supercapacitors are batteries, too!

- > 10 kF capacitors now available commercially
- Can be used for transportation
- Main advantage: very rapid recharging
- Main disadvantage: very frequent recharging needed



FIGURE 24.33 Supercapacitor-powered bus recharging at a bus stop in Shanghai, China.

W. Bauer and G. D. Westfall



Lithium-Based Battery Supply Chain

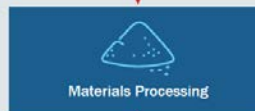
UPSTREAM

- Mining and extraction of materials including lithium, cobalt, nickel, and graphite



MIDSTREAM

- Additional processing for battery-grade materials
- Cathode/anode powder production
- Separator production
- Electrolyte production
- Electrode and cell manufacturing



DOWNSTREAM

- Pack manufacturing
- End-of-life recycling and reuse

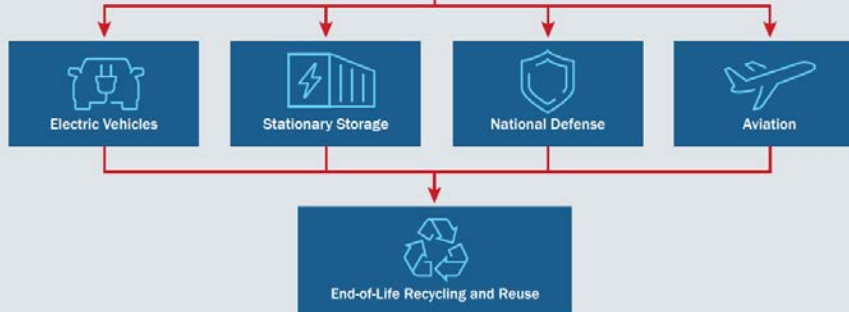


FIGURE 5. Steps in the lithium-battery material supply chain.



Availability of battery raw materials

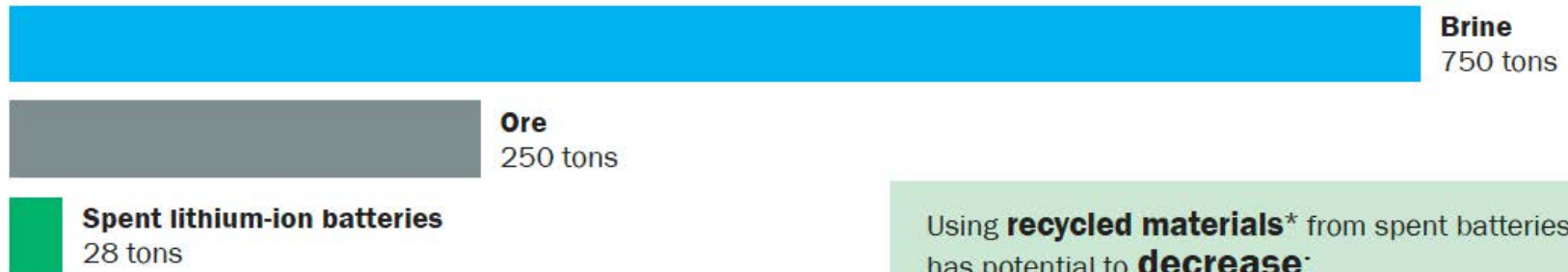
Element	U.S. Reserves (1000 Metric tons)	World Reserves (1000 Metric tons)	Total Manufacturing Capacity with U.S. reserves (GWh)	Total Manufacturing Capacity with world reserves (GWh)
Lithium	750	21,000	7470	209,163
Cobalt	53	7100	703	94,164
Nickel	100	94,000	167	156,510
Manganese	230,000	1,300,000	3,271,693	18,492,176

Source: Argonne National Laboratory derived from USGS mineral commodities summaries (2021) and simulations using BatPaC 4.0 for Li-ion batteries with $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$ cathode.



Recyclability

1 ton of battery-grade **lithium** can come from:



1 ton of battery-grade **cobalt** can come from:



Using **recycled materials*** from spent batteries has potential to **decrease**:



- Costs by **40%**
- Energy use by **82%**
- Water use by **77%**
- SO_x emissions by **91%**

*Assumes a direct recycling method

FIGURE 7. Benefits of recycling for lithium-ion batteries. Data from Argonne National Laboratory's ReCell Center, 2019.³³



Battery price: Getting gradually lower

Figure 1: Volume-weighted average pack and cell price split

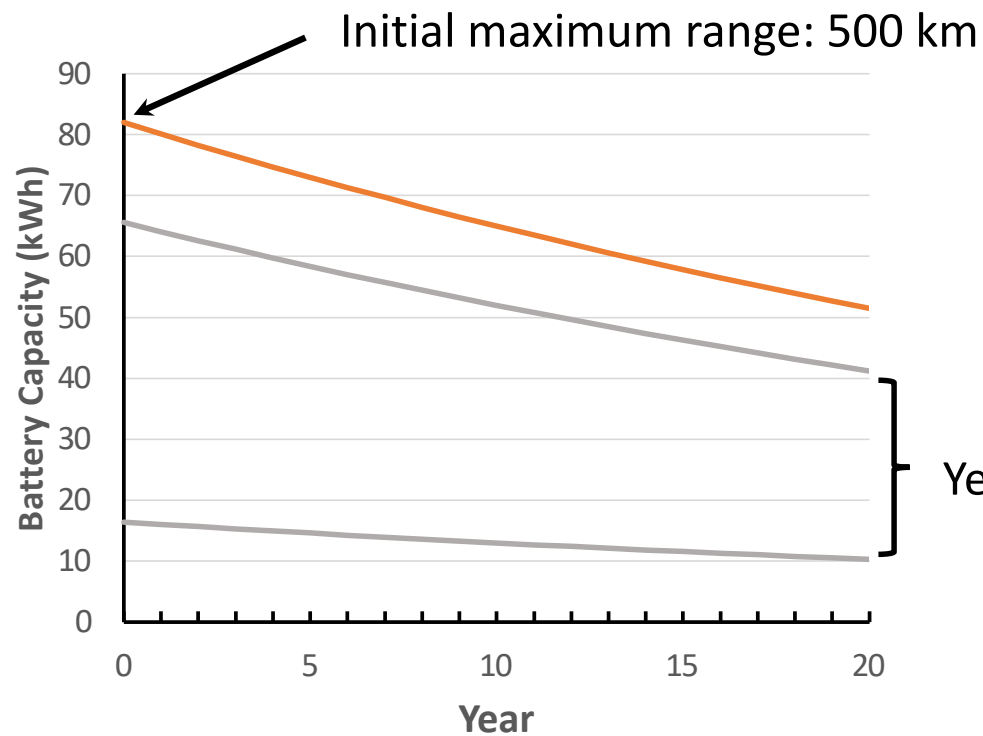
real 2021 \$/kWh



Source: BloombergNEF.



Battery Degradation



Data from 6,300 EVs with liquid-cooled batteries in Geotab fleet:
2.3% average degradation/year

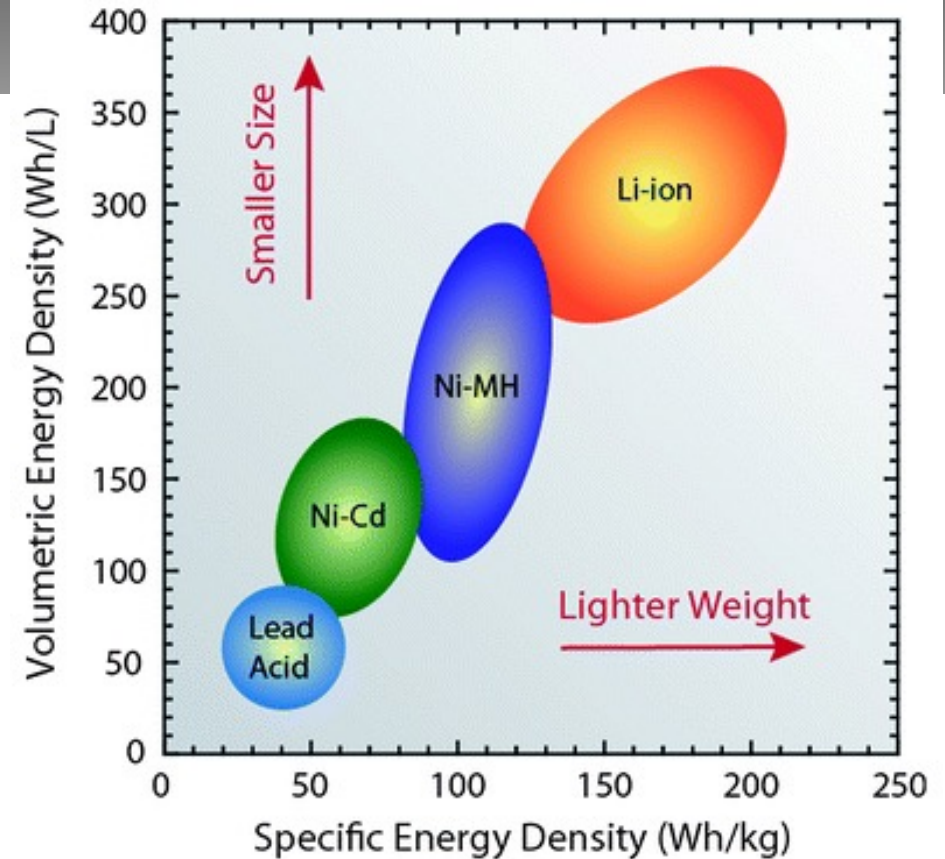


Battery Energy Density

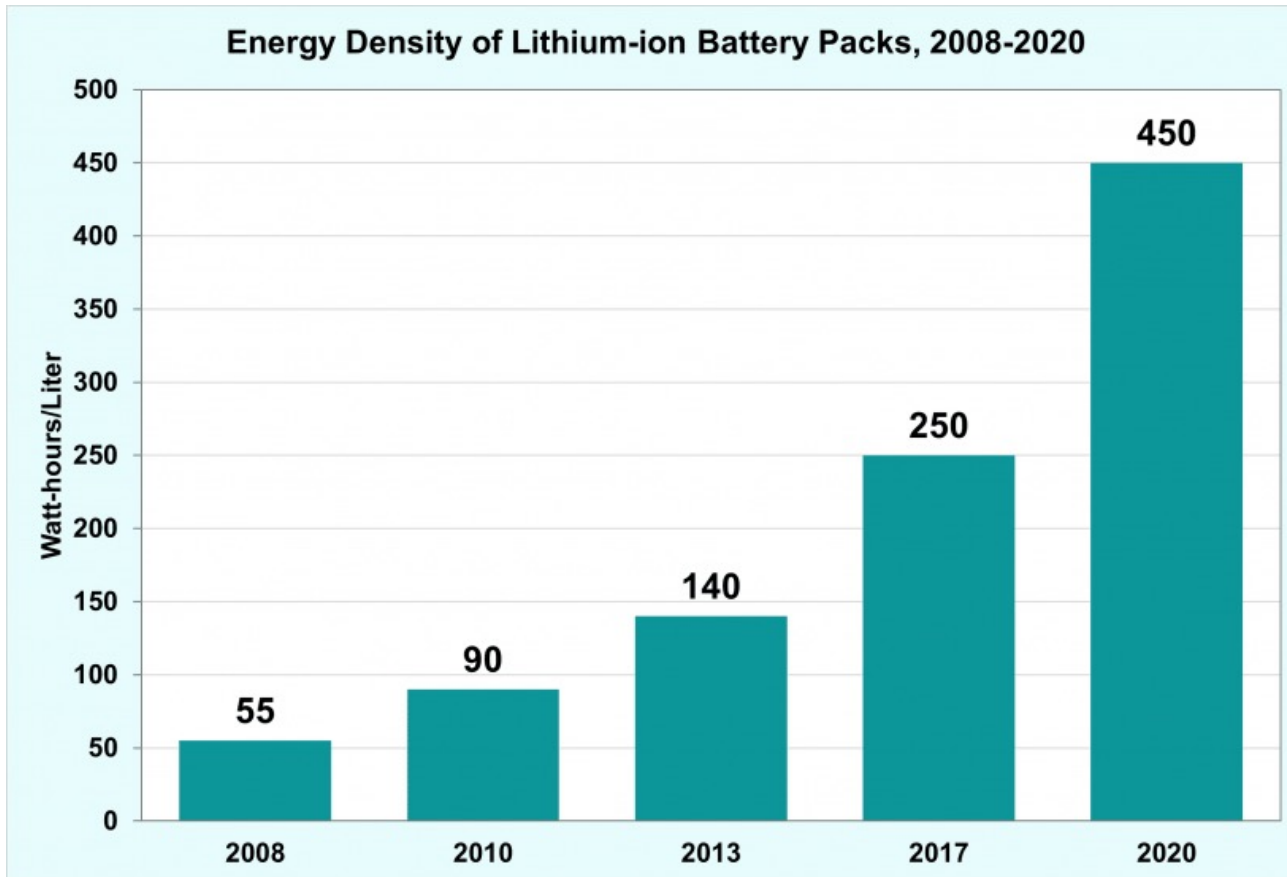
For comparison

Gasoline:

- 12200 Wh/kg
- 9700 Wh/L



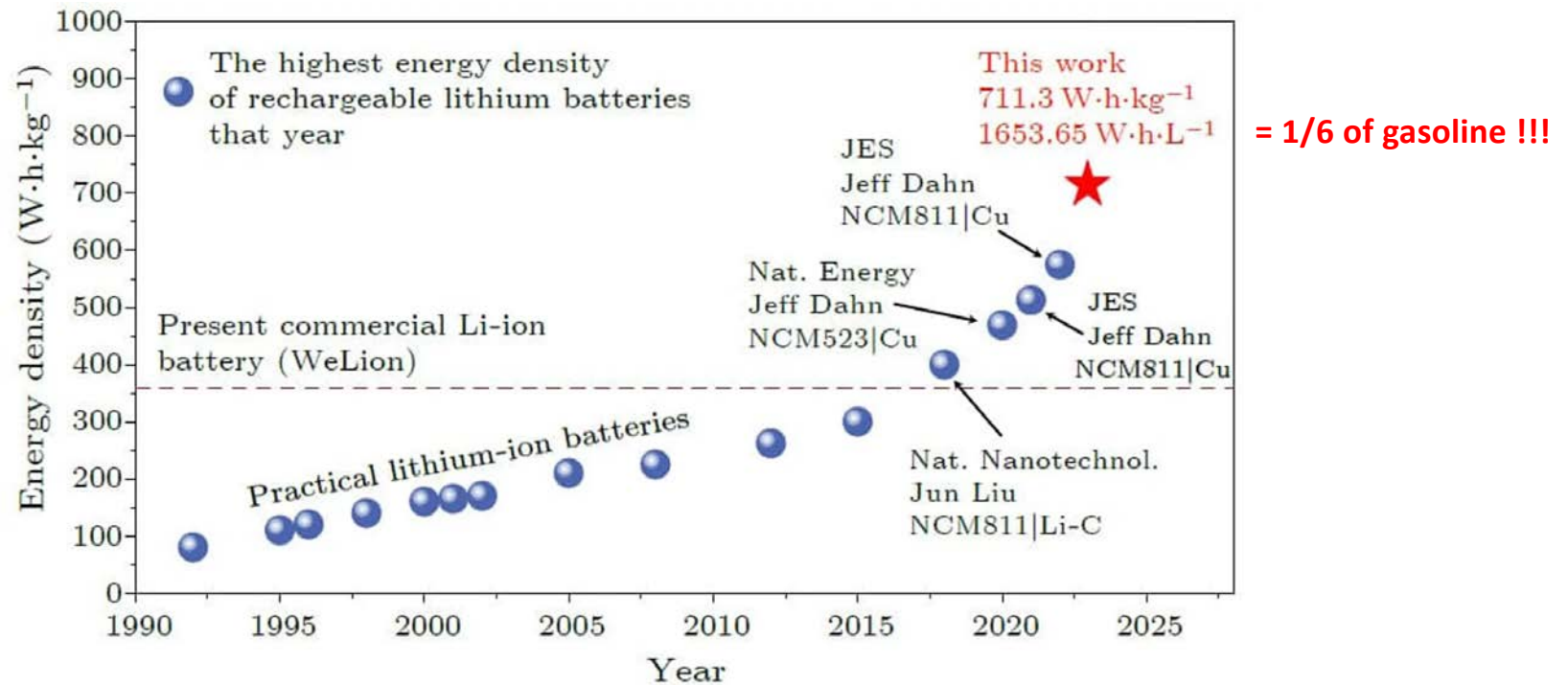
Roberta DiLeo, RIT Ph.D. Thesis, 2012 (Fig 1a)



<https://www.energy.gov/eere/vehicles/articles/fotw-1234-april-18-2022-volumetric-energy-density-lithium-ion-batteries>



Current world record battery lab modules



Quan Li *et al* 2023 *Chinese Phys. Lett.* **40** 048201

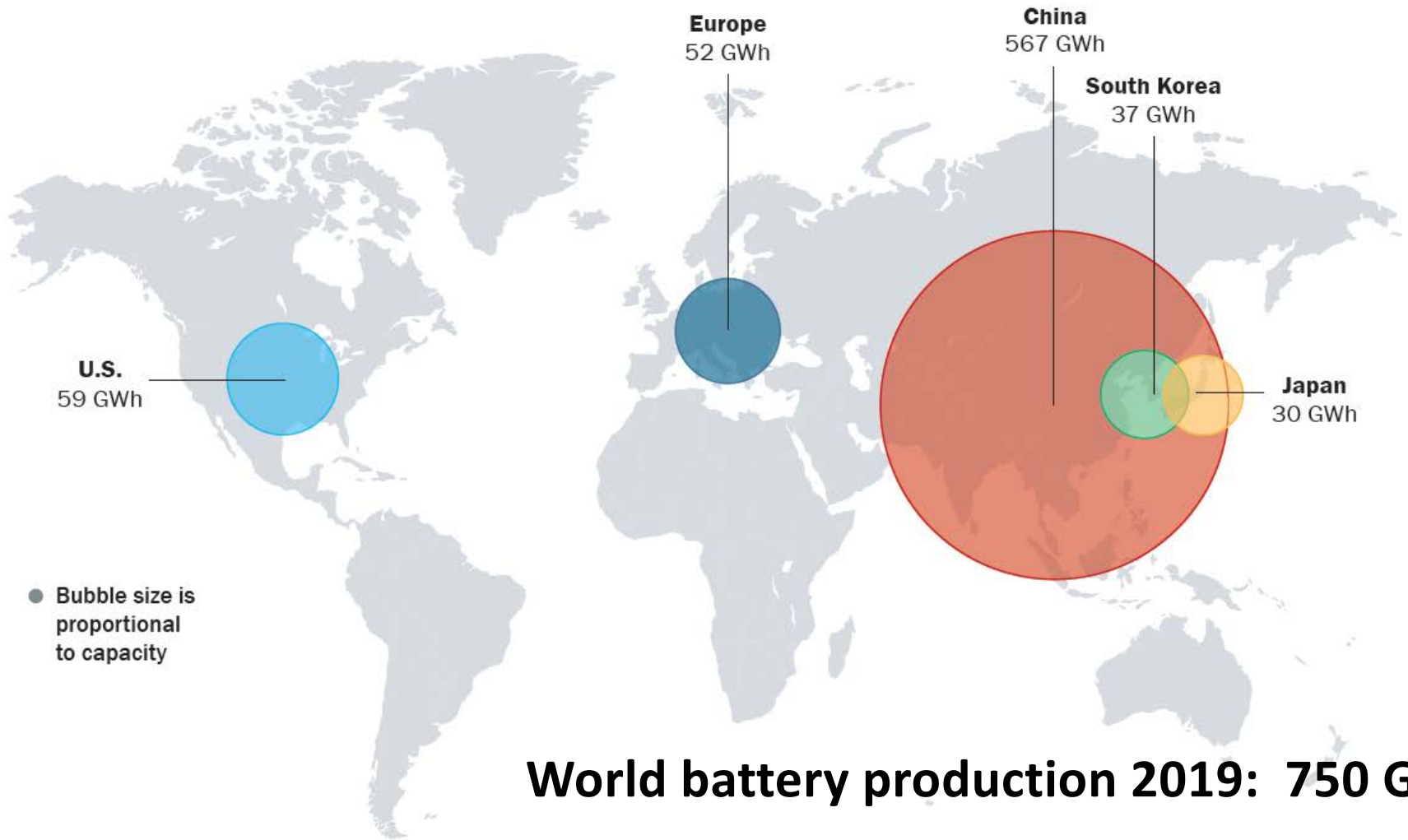


FIGURE 6. Cell manufacturing capacity by country or region.

Source: "Lithium-Ion Battery Megafactory Assessment", Benchmark Mineral Intelligence, March 2021.³²



World Battery Production: Near Future

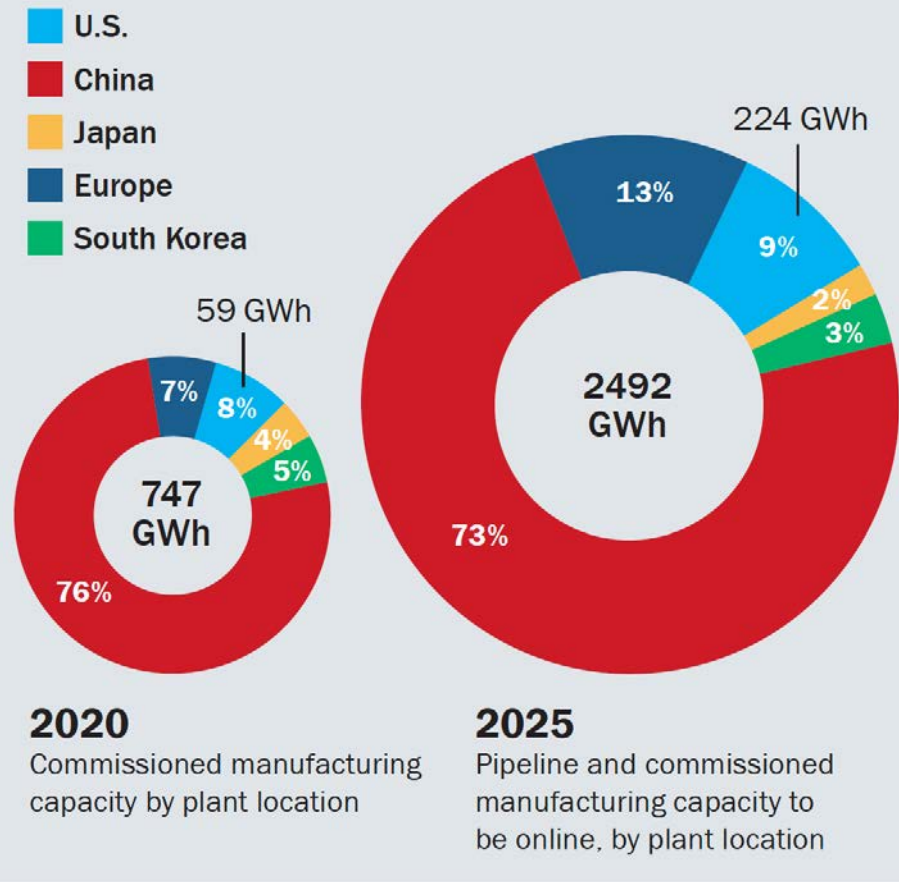
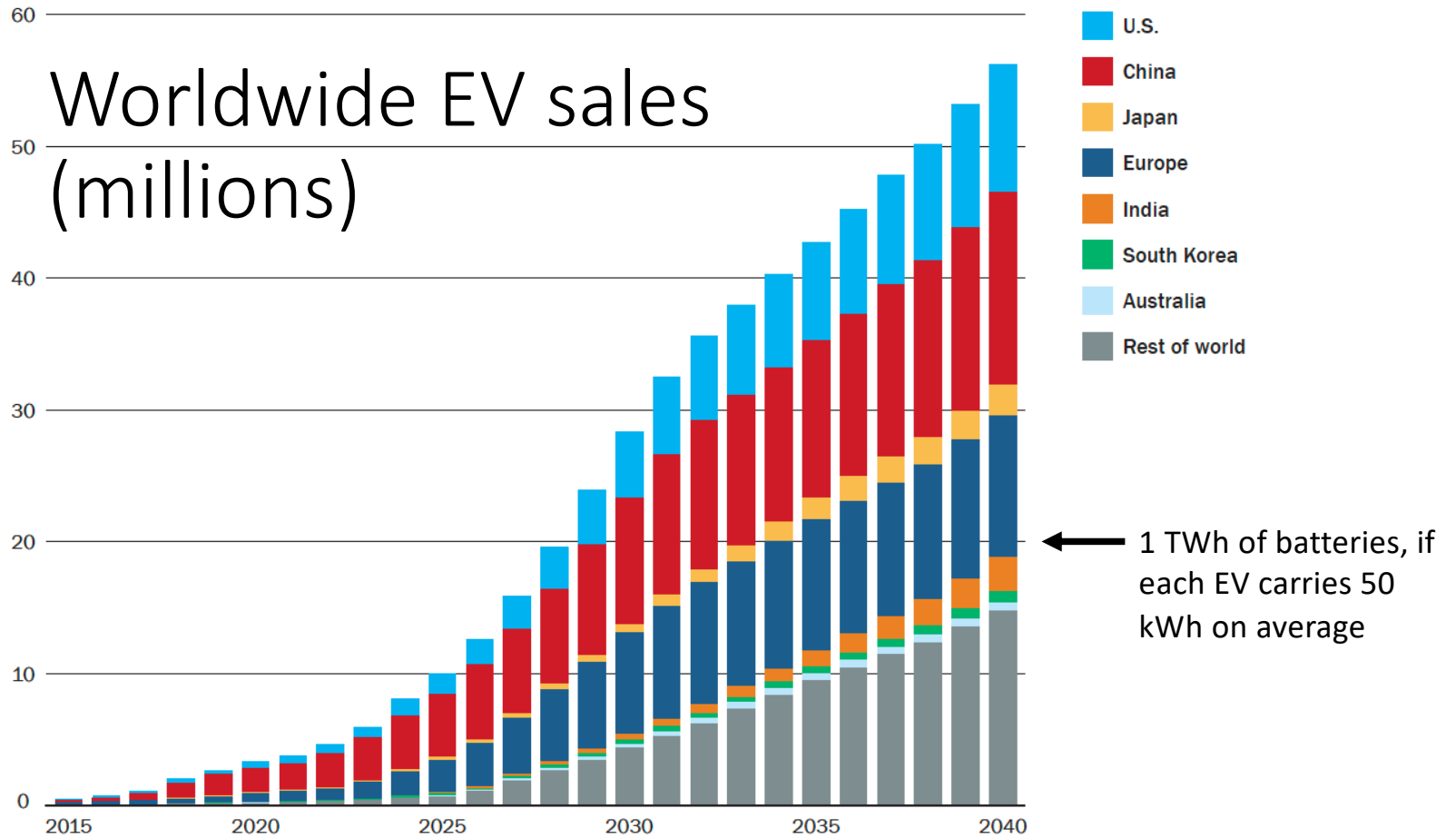


FIGURE 3. Cell manufacturing capacities.
Source: "Lithium-Ion Battery Megafactory Assessment", Benchmark Mineral Intelligence, March 2021.



20 June 2023

FIGURE 1. Annual Sales of Passenger EVs (Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs)).
Source: BloombergNEF Long-Term Electric Vehicle Outlook 2019.¹⁶



How will we recharge the EV batteries, and when?



20 June 2023

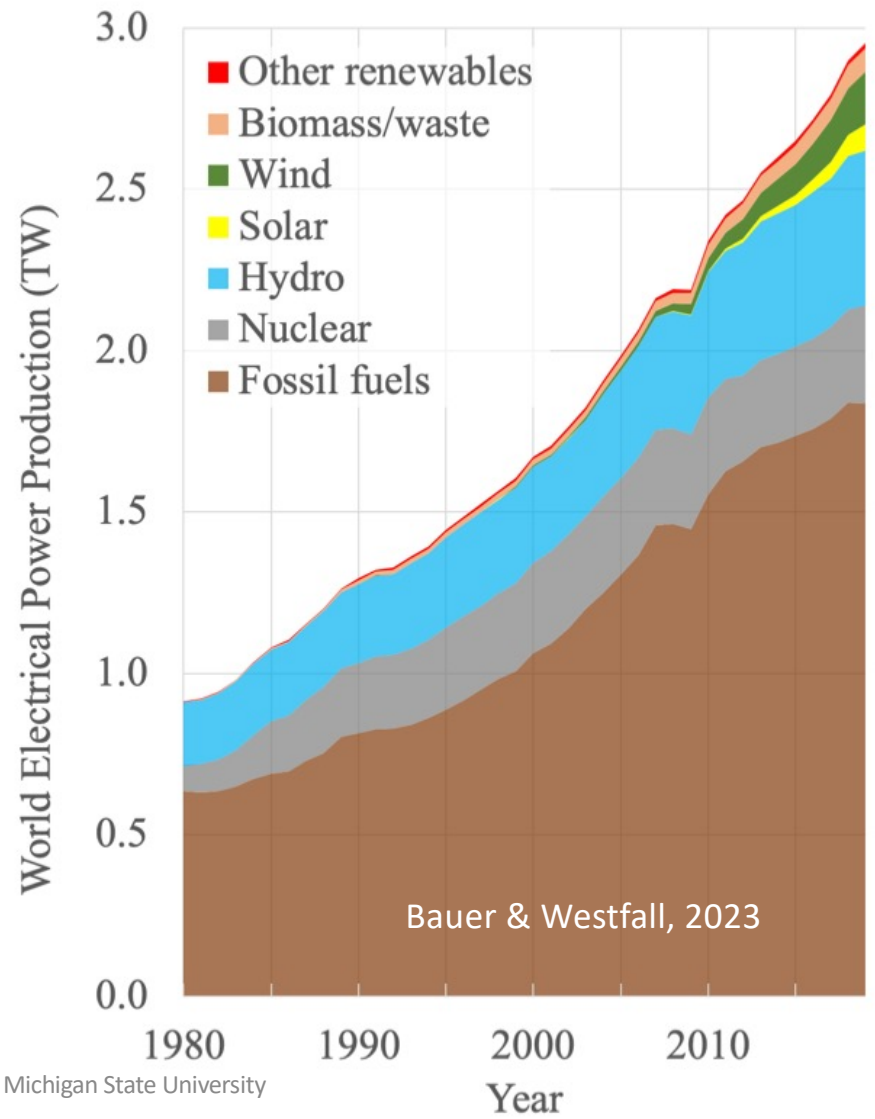
W. Bauer, Michigan State University



- Passenger cars are (usually) manageable:
- Connect to your home charger
 - Set schedule for low demand times and/or high availability of renewable power
 - Save money & help out the grid



World Electricity Production

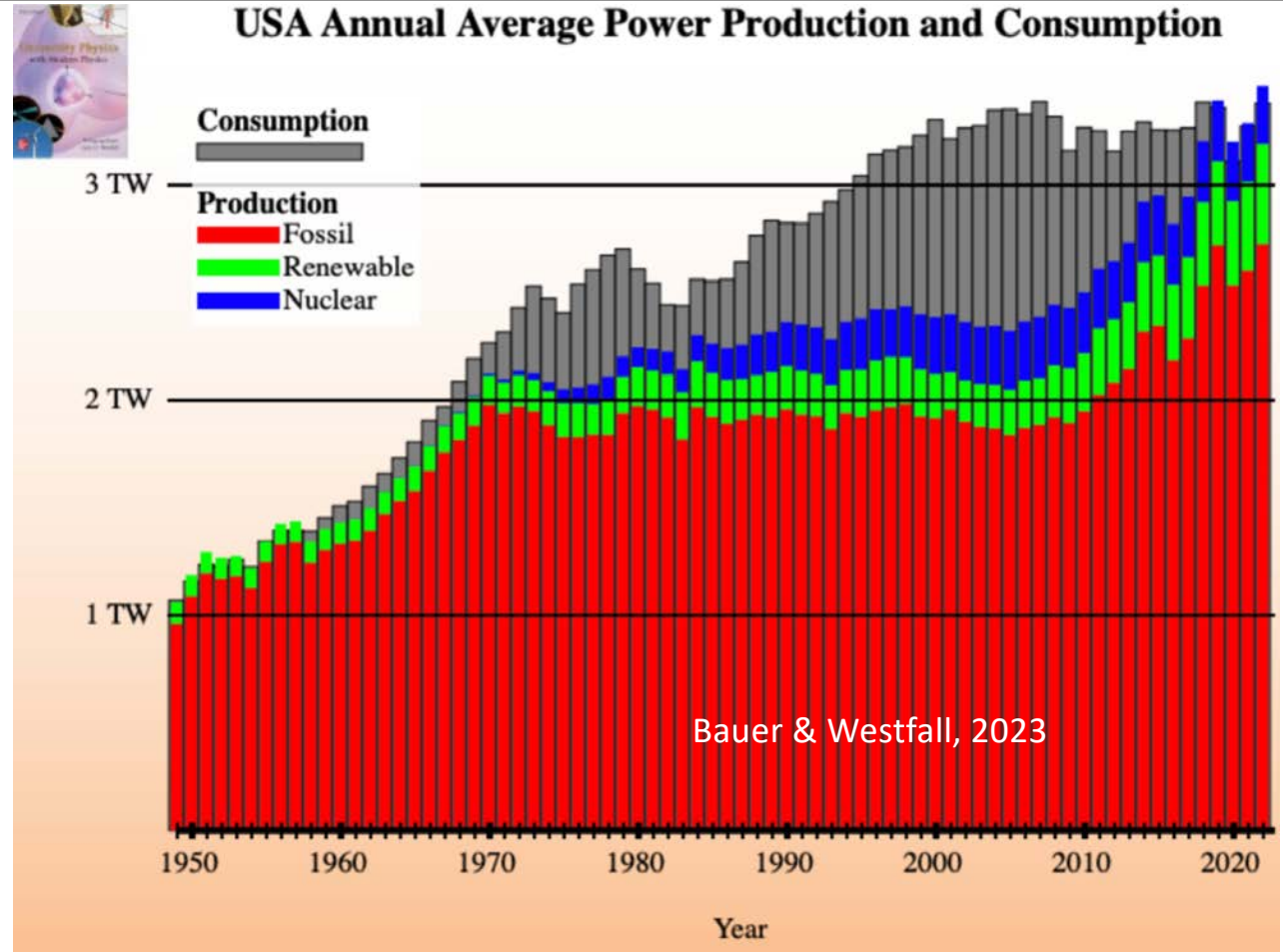




USA

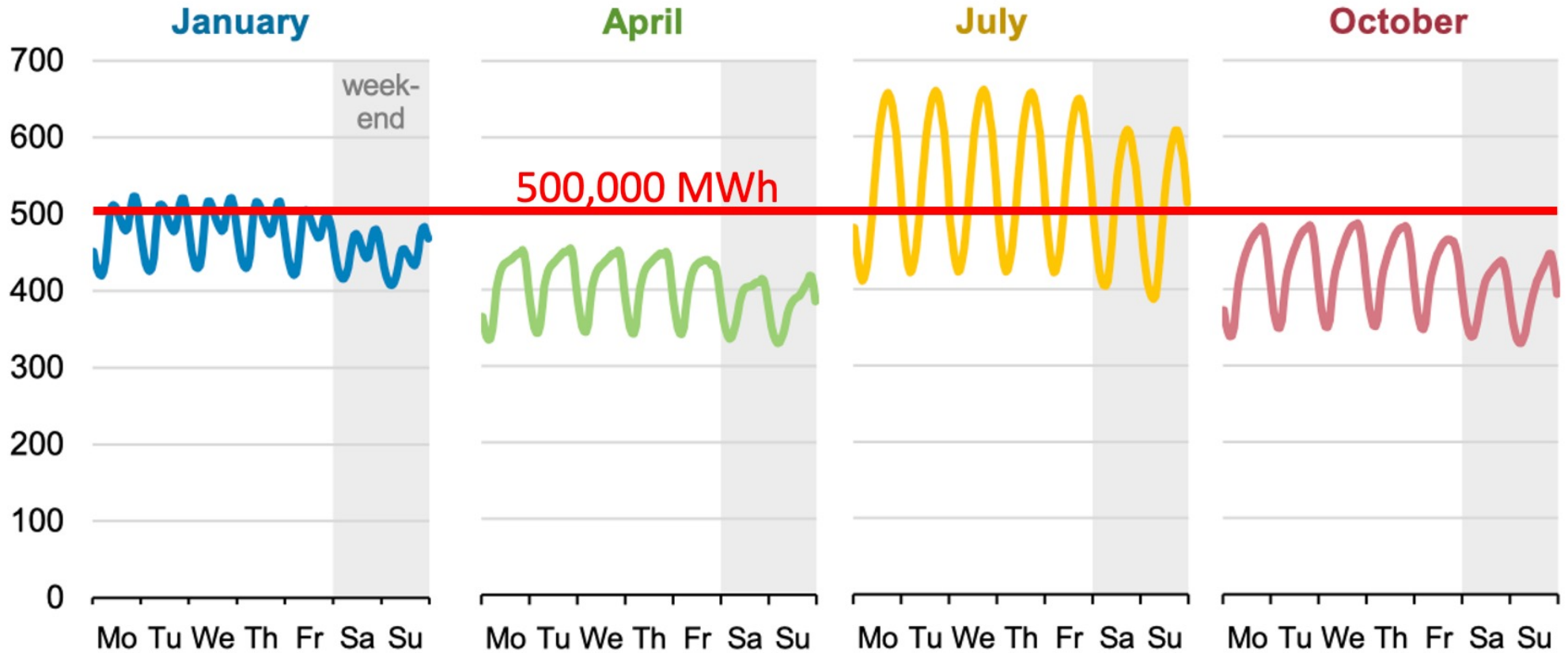
All sources:

- Electricity
- Heating
- Industrial production
- Transportation



Average hourly U.S. electricity load during typical week, selected months

million kilowatthours



Source: U.S. Energy Information Administration, [U.S. Hourly Electric Grid Monitor](#)

Note: Data shown represent the average aggregate U.S. hourly load (Eastern Standard Time) by day of the week for the months indicated between 2015 and 2019.



EV charging: commercial vehicles



Creator: Ava_Marie | Credit: Getty Images/iStockphoto

4 million heavy duty (class 8) trucks in the USA
(3.4 M truck drivers)

Numerical example:

Assume only 20% electrification

- 500 kWh of batteries on average truck
- ~ 250 miles of range (= ½ of daily driving)
- 800 GWh/day needed to recharge trucks
- Charging overnight at truck stops ✓
- Recharging at lunch time (1 hour)
 - Need 500 kW ultra-fast chargers
 - Additional load of 400 GW on grid during 1 hour ✗



Implications for Grid

- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
 - Most likely reciprocal internal combustion engines burning natural gas



MSU's new 30 MW RICE plant: **need 13000 of these**



Implications for Grid

- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
 - Most likely reciprocal internal combustion engines burning natural gas
 - Could be biogas

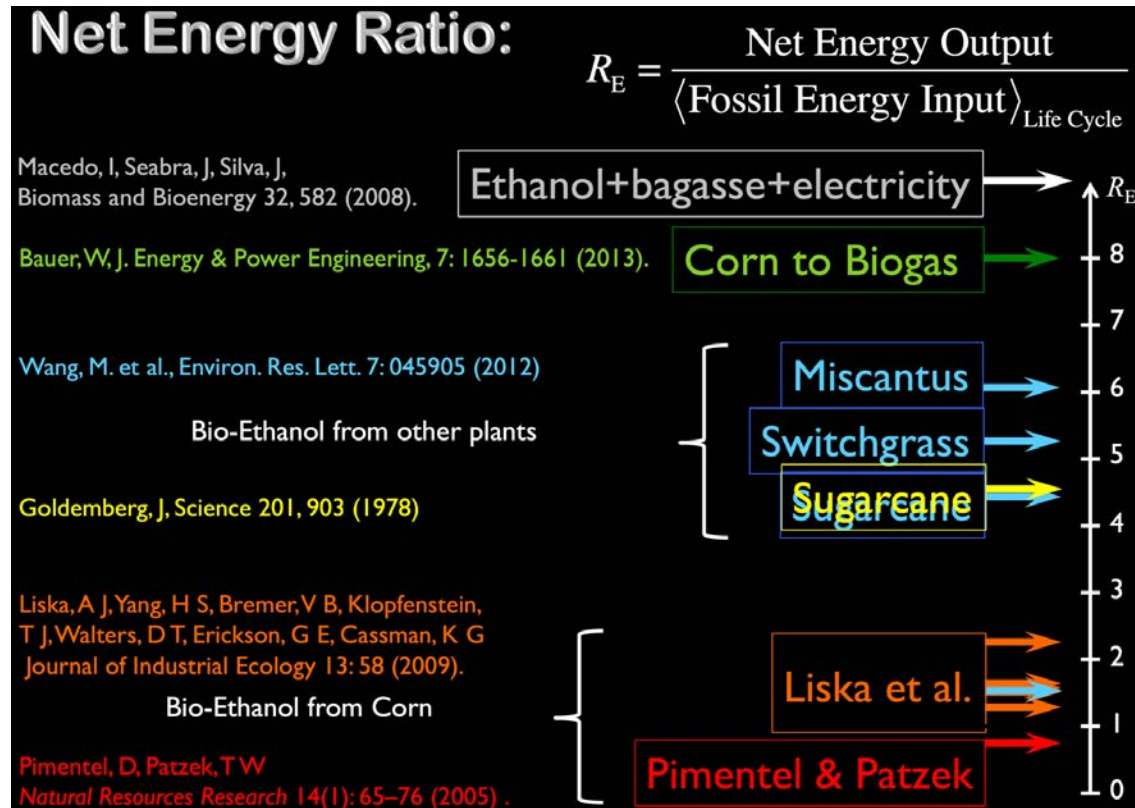


Our German 1 MW biogas plant: **need 400000 of these**



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Warning: even biofuels are not free of fossil fuels!!!



Implications for Grid

- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
 - Most likely reciprocal internal combustion engines burning natural gas
 - Could be biogas
- Alternatively: storage



Ludington pump storage plant: **Need 200 of these**



Implications for Grid

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<https://www.energyvault.com/project-cn-rudong>

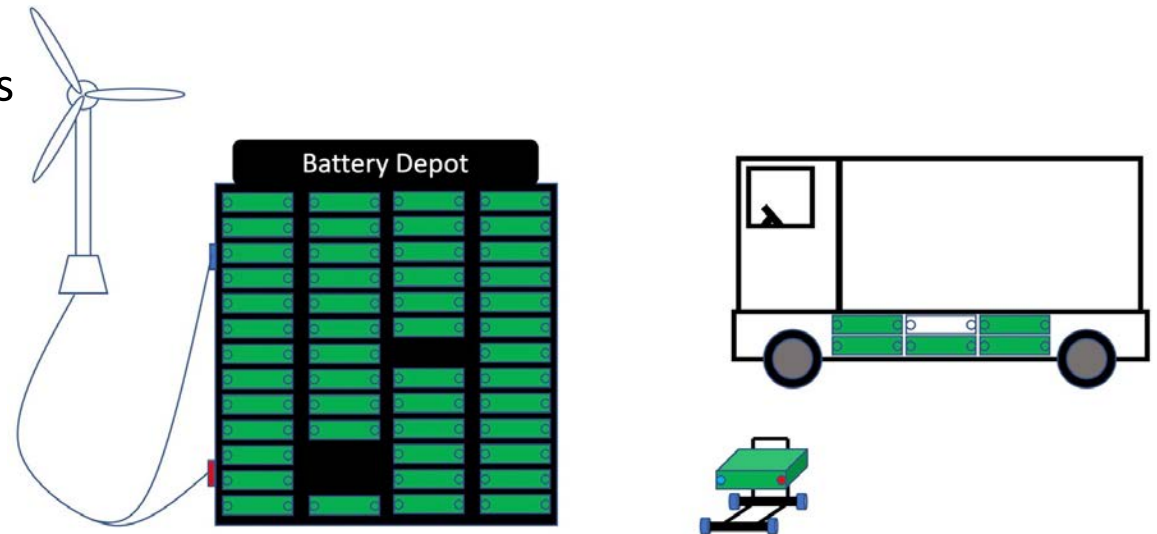
25 MW Energy Vault in Rudong, China: **Need 16000 of these**



Better approach: charge batteries outside of EVs

Advantages:

- Extremely rapid recharge of vehicles
 - A few minutes
 - Comparable to filling tank with gas
- Easy replacement of degrading batteries over time
- Perfect utilization of renewable power sources
 - Batteries can be recharged when the wind blows or sun shines
 - Mitigates intermittency in renewable power production



Swappable individual battery modules
Similar to power tool recharging



GM Ultium Platform



<https://www.chevrolet.com/new-roads/electric/next-gen-ultium-platform>

Ultium Module:

8.88 kWh

32.7 kg

14.5 L

270 Wh/kg

610 Wh/L

Challenge:

Make individual
battery
pouches
swappable



Nio: Swap out entire battery pack

- Nio offers > 1300 swapping stations
 - Now has 16 battery swap stations in Europe
- Also offer conventional battery chargers
- 60% of users opt for swapping



<https://electrek.co/2023/05/16/nio-and-shell-open-first-ev-battery-swap-station-in-europe>



<https://www.nio.com/nio-power>



Current project at MSU

- Design new electric vehicle with swappable batteries
- 30 kg modules, which can be swapped rapidly by a single person
- First prototype ready by end of 2023





Conclusions: Battery Swapping

- Eliminates range anxiety
- Minimizes recharging time
- Gradually modernizes all batteries
 - New battery performance increases 5%-10% per year
 - Year 20 EV range > than initial advertised range
- Battery depots provide giant energy storage reservoir for grid
 - 1 TWh to 10 TWh
 - Avoids losses from intermediate energy storage in other forms (pumped hydro, gravity, fixed battery)
 - Avoids the need for peaker plants
- Eliminates the need for intermittency mitigation of renewables



Thank you

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